THE ORIGIN AND SIGNIFICANCE OF THE CCAM LINE: EVIDENCE FROM CHONDRULES AND DARK INCLUSIONS IN ALLENDE (CV3).

R. C. Greenwood[1], I.A. Franchi[1]; M. E. Zolensky[2], P.C. Buchanan[3]. [1]Planetary and Space Sciences, The Open University, Milton Keynes MK7 6AA, UK (r.c.greenwood@open.ac.uk). [2]ARES, Johnson Space Center, Houston TX, USA.[3]Kilgore College, Kilgore, Texas 75662 USA.

Introduction: The process responsible for the mass independent oxygen isotope variation observed in Solar System materials remains poorly understood. While self-shielding of CO, either in the early solar nebula [1,2], or precursor molecular cloud [3], appears to be a viable mechanism, alternative models have also been proposed [4].

An important aspect of this problem relates to the interpretation of various reference lines on oxygen three-isotope diagrams. The Carbonaceous Chondrite Anhydrous Mineral (CCAM) line, derived predominantly, but not exclusively, from analyses of components in the Allende (CV3) meteorite, is the most widely used reference and has a slope of $0.94\pm0.01(2\sigma)$ [5,6]. However, the fundamental significance of the CCAM line has been questioned by [7]. Based on the results of a UV laser ablation study of an Allende CAI, these authors suggested that a line of exactly slope 1 was of more fundamental significance. They pointed out that almost all Solar System materials, with the exception of the R chondrites, plot either on, or to the right of the slope 1 line. They went on to suggest that this variation could be explained if the primitive oxygen isotope composition of the Solar System was represented by the slope 1 line, with subsequent mass fractionation or isotopic exchange shifting compositions away from this line to the right. The fact that a highly $^{17,18}O$-enriched phase ($\delta^{18}O$ and $\delta^{17}O$ = ~ +180‰) within the matrix of the primitive chondrite Acfer 094 plots on the extension of the slope 1 line lends additional support to the primordial significance of this reference line [8]. With the aim of understanding the relationship between the CCAM and other reference lines we have undertaken a detailed study of chondrules and dark inclusions from Allende.

Materials and methods: As part of this study intact chondrules (n=30) were extracted from Allende (CV3) whole-rock fragments under a binocular microscope. Adhering matrix material was abraded from the chondrules using stainless steel hand tools. Material from well characterized Allende Dark Inclusions (DIs) (n=11) have also been analyzed. Preliminary results of this DI work were reported in [9]. In addition to Allende DI samples, we have also analyzed material from the Efremovka (CV3reduced) inclusion E-80 [10].

Oxygen isotope analysis was performed by infrared laser-assisted fluorination [11]. All analyses were obtained on untreated whole rock samples (0.5-2 mg). System precision, as determined by replicate analyses of our internal obsidian standard, is: ±0.05‰ for $\delta^{17}O$; ±0.09‰ for $\delta^{18}O$; ±0.02‰ for $\Delta^{17}O$ (2σ).

Results: Allende DIs analyzed in this study plot on a well-defined linear trend with a somewhat shallower slope than the CCAM line (Fig. 1). The Allende DI analyses of [6] are also shown in Fig. 1 and plot on a similar trend. Less altered chondrule-bearing clasts (Types A and A/B) tend to plot closer to bulk Allende than the more altered Type B inclusion, with the matrix-rich Type C clasts plotting in a relatively narrow intermediate position along the array (Fig. 1).

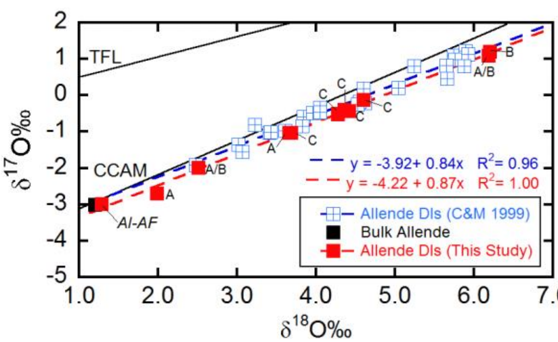

Fig. 1 Oxygen isotopic composition of Allende Dark Inclusions.

Compared to Allende DIs, inclusions from the CV3 reduced subgroup (Efremovka, Leoville, Vigarano) fall on a distinct, well-defined trend with a relatively shallow slope (Fig. 2) (All analyses from the literature [6, 10], except E-80 (this study)). This trend is similar to that seen in CM2 chondrites (Fig. 2), to which DIs have sometimes been compared [12].

In contrast to the DIs, chondrules extracted from Allende (Fig. 3) plot to the left of the CCAM line. This feature is also clearly seen in the Allende chondrule data of [13]. If chondrules that plot close to the TFL are included our Allende chondrule data define a trend with a slope that is somewhat steeper than 1 (Fig. 3). Excluding this small cluster of ^{16}O-poor chondrules, the remaining data points lie roughly equidistant between the CCAM and PCM lines (Fig. 3) and define a distinct linear array (($y = -3.45 + 0.97x$ $R2 = 0.98$).

Discussion: In its original formulation the CCAM line was calibrated using analyses not only from Allende CAIs, but also Allende chondrules and dark inclusions [5]. In addition, a limited number of analyses

of non-Allende carbonaceous chondrite components were also included [5]. The CCAM line includes materials with distinct formational and secondary histories. It is therefore not surprising that individual components in Allende, such as chondrules and dark inclusions, will display systematic deviations from it.

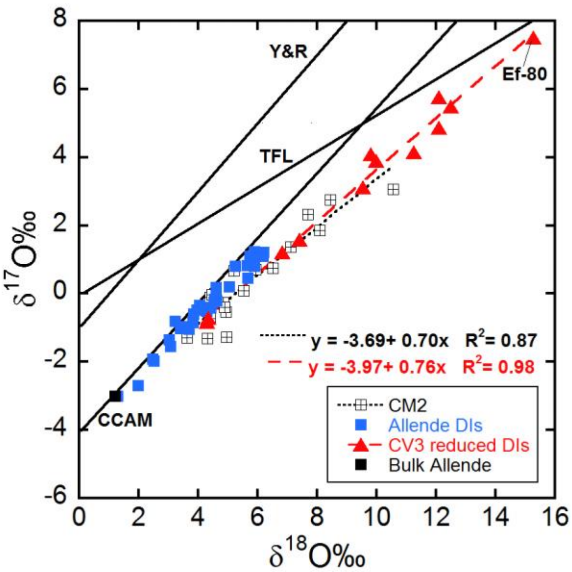

Fig. 2 Oxygen isotope composition of Allende DIs (This study) [6]; CM2 Falls and finds (all data OU); CV3 reduced DIs [6, 10] (E-80: This Study).

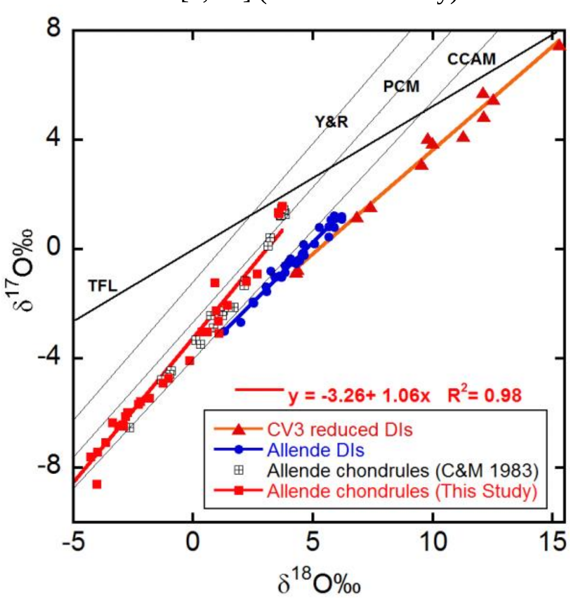

Fig. 3 Oxygen isotopic composition of chondrules and DIs from Allende shown in relation to various reference lines. PCM = Primitive Chondrule Minerals line [14, 15].

DI data from Allende presents an interesting paradox in that it defines a more limited and steeper trend then that of inclusions from the less altered CV3 reduced samples (Fig. 2). Thus, CV3 reduced DIs appear to preserve more clear cut evidence of aqueous alteration than those from the more heavily altered Allende meteorite. Raman spectroscopic analysis of organic matter suggests that the CV3 chondrites experienced a significant range in thermal metamorphism, with Allende >3.6 and Efremovka, Leoville and Vigarano = 3.1 to 3.4 [16]. One possibility is that the more intense thermal metamorphism experienced by Allende resulted in relatively rapid expulsion of pore fluid and hence less intense hydrothermal alteration compared to CV3 reduced DIs. However, this explanation seems at odds with detailed mineralogical observations from Allende DIs which suggest that they experienced prolonged aqueous alteration followed by dehydration [17, 18, 19], processes that should both have produced significant heavy oxygen isotope shifts [20, 21]. It appears more likely that subsequent to significant hydrothermal alteration Allende DIs experienced a phase of partial oxygen isotope reequilibration.

There is growing evidence that chondrules from relatively pristine carbonaceous chondrites such as Acfer 094, MET 00426 and QUE 99177 define a distinct trend termed the PCM line, that is roughly equidistant from the CCAM and Y&R lines (Fig. 3) [14, 15]. Compared to the PCM line the majority of chondrules in Allende are shifted to the right on an oxygen three-isotope diagram (Fig. 3). This most likely reflects mass fractionation in response to secondary alteration.

Conclusions: Chondrules and DIs in Allende demonstrate that the CCAM line, while useful for reference purposes, is not in itself of primary significance. In agreement with previous studies, we conclude that primary oxygen isotope distribution is better represented by a line of steeper slope than the CCAM [7]. However, this does not preclude the possibility that multiple slope 1 lines may be valid. Additional detailed work using components from pristine samples is required to evaluate further the processes that produced the mass-independent oxygen isotope variation observed in early Solar System materials.

References: [1] Clayton R. N. (2002) *Nature 415*, 860-861. [2] Lyons J. R. and Young E. B. (2005) *Nature 435*, 317-320. [3] Yurimoto H. and Kuramoto K. (2004) *Science 305*, 1763-1766. [4] Dominguez G. (2010) *Ap. J. Lett. 713*, L59-L63.[5] Clayton R. N. et al. (1977) *EPSL 34*, 209-224. [6] Clayton R. N. and Mayeda T. K. (1999) *GCA 63*, 2089-2104. [7] Young E. D. and Russell S. S. (1998) *Science 282*, 452-455. [8] Sakamoto N. et al. (2007) *Science 317*, 231 – 233. [9] Greenwood R. C. et al. (2015) *46th LPSC* abstract #2975. [10] Krot A. N. et al. (1999) *MAPS 34*, 67-89.